

Battlefield Awareness Via Synergistic SAR and MTI Exploitation

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ABSTRACT

“Battlefield awareness” is critical to the success of future military operations. Existing and new sensor platforms will provide the necessary surveillance data; DARPA is developing the systems needed to turn the sensor data into meaningful information for the commanders. A central thrust of these efforts exploits the synergistic relationship between SAR and MTI radar. Used together, they offer comprehensive coverage of the battlefield.

THE REQUIREMENT FOR WIDE-AREA SURVEILLANCE

To prevail in the diverse arenas of future conflicts, the United States and its allies must achieve “dominant battlefield awareness” which means, simply stated, a knowledge of everything occurring on the battlefield [1]. To apply their assets optimally, the commanders in the theater must know the locations, identities and, ideally, the intentions of the enemy forces. The challenge to the R&D community is to develop the systems and technologies to provide battlefield awareness [2].

Sensors, of course, generate the data about events on the battlefield, and radar, in particular, must play a major role because of its day-and-night, all-weather capability [3,4]. Synthetic Aperture Radar (SAR) can provide high-resolution imagery of stationary objects. Moving Target Indicator (MTI) radar can detect and locate moving targets. Working together, they offer the potential for comprehensive coverage of vehicle targets on the battlefield.

The primary distinctions between the historical use of sensors, in reconnaissance roles, and tomorrow’s surveillance needs are: (1) the size of the areas that must be searched; (2) the sensor resolution required; and (3) the rapidity and frequency with which the search must be done. To support battlefield awareness, sensors will be asked to cover regions larger than 400 km on a side at high resolution, with a revisit time of significantly less than an hour. We label an operation of this scale “wide-area surveillance”.

During Desert Storm, the U.S. and its Coalition allies stressed the limits of existing sensor systems by attempting to perform wide-area surveillance of the vast Iraqi desert. The U-2 and Joint STARS¹ were employed in the theater to gather the needed information. Although significant intelligence needs were met by the surveillance operation, serious deficiencies were

noted [5]. Shortfalls included the limited availability of timely sensor coverage, the lack of wide-area, high-resolution imagery, and the inability to discriminate between moving vehicles of differing type.

NEW PLATFORMS AND SENSORS

Largely in response to the shortfalls uncovered in Desert Storm, the U.S. has begun aggressive development of additional surveillance capabilities, with particular emphasis on unmanned aerial vehicles (UAVs) because of their relatively low cost [6]. Two of the UAVs — the radar-equipped Global Hawk and Dark Star — will operate at high altitude performing wide-area surveillance. An unprecedented quantity of data will be produced by these systems. For example, the SAR will generate a ten-kilometer-wide swath of stripmap imagery with a spatial resolution of one meter, and, as appropriate, spotlight mode images at 1/3-meter resolution. Simple arithmetic shows that one UAV can cover up to 150,000 km² per day, generating almost two imagery frames per second, at full resolution, on a 1024-by-1024 pixel display. No single human can digest this enormous data rate.

Of course, the commanders in the field do not need raw data; they need concise, coherent and comprehensive information, derived from the data. Significant advances in the surveillance infrastructure and processing systems will be required to extract the information from the sensor data and disseminate it in a timely manner to the theater commanders.

DARPA VISION AND PRIORITIES

The Defense Advanced Research Projects Agency (DARPA) has the mission to maintain the U.S. military’s technological advantage over the rest of the world. DARPA must pursue the high-risk, high-payoff technologies, and therefore, consistent with this charter, has taken on the challenge of developing systems and technologies to turn sensor data into the information needed for a comprehensive picture of the battlefield.

Multiple frontiers must be pushed. A low-frequency, foliage-penetration (FOPEN) radar will be built to detect camouflaged or foliage-covered targets. The DARPA Semi-Automated IMINT Processing (SAIP) program is incorporating Automated Target Recognition (ATR) algorithms and false-alarm mitigation techniques into a system to help the image analysts (IAs) identify targets and reject clutter in SAR imagery. A technique called High-Definition Imaging is used to generate higher resolution than possible with conventional processing.

Advanced algorithms are under development which will extract information from MTI data as well. Certain targets may

¹ Although JSTARS had not yet reached full operational status when it was deployed to the Persian Gulf, it proved extremely useful for generating information about force movements on the battlefield, including the dramatic retreat of Iraqi armor from Kuwait.

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have unique motion patterns which can be recognized. Further, if the MTI radar has a high-range-resolution (HRR) waveform, moving vehicles may be identifiable by their distinctive range profiles. Algorithms also are being developed to generate two-dimensional inverse SAR (ISAR) imagery of moving vehicles [7,8]. These and other techniques for recognizing targets in MTI data are being developed by the DARPA Moving-Target Exploitation (MTE) program.

MTE has a goal of transforming traditional MTI sensors, which simply detect movers, into systems capable of classifying vehicles and performing birth-to-death tracking. MTE is particularly attractive because moving targets: (1) are easily detectable due to their Doppler shift relative to the background; (2) are unlikely to be concealed or camouflaged; and (3) have known aspect angles if on-road. Further, the population of potential false alarms is limited to other moving vehicles.

The sensor-exploitation programs (SAIP and MTE) have the goal of reducing false alarms to a level manageable by the image analysts and attack assets. In the near term, state-of-the-art technologies will be integrated into existing systems. For example, template-based ATR algorithms will be incorporated into image-analyst workstations. More advanced technologies, such as model-based ATR, will be included as they mature.

Many sensors will be present in the theaters of future conflicts, including SAR, MTI, SIGINT for collecting radiated signals, electro-optical sensors, and perhaps even acoustic devices. Algorithms are being constructed in the DARPA Dynamic Multi-user Information Fusion (DMIF) program to correlate, fuse and track the information from these disparate sensors.

DARPA has also initiated a program called Advanced Cooperative Collection Management (ACCM) to develop tasking logic which will optimize the use of diverse sensor capabilities. Algorithms will prioritize information needs, assign collection tasks to sensors, dynamically plan platform trajectories, and schedule sensor tasks to meet the demand and assure the appropriate sensor mode is used from the best viewing geometry at the right time.

Finally, the problem of limited accessibility and latency of sensor products is being addressed by the DARPA Battlefield Awareness and Data Dissemination (BADD) program.² This effort is developing an infrastructure using the Global Broadcast Service to make a vast library of sensor and other products available to the users in the field. For example, via portable computers (called Warfighter's Associates), an Information Dissemination Server, and satellite links, users in the field can request a variety of data, including imagery. If the data exists, the user will receive it shortly after placing the request. If it does not exist, it will be collected and subsequently transmitted.

As illustrated in Figure 1, all of these technologies being pursued by DARPA will work together within a "system of systems" to task the sensors, exploit the resulting data, fuse it in an intelligent manner, and disseminate the information to the users. The remainder of this paper focuses on one critical

element: the value of using SAR and MTI together for surveillance against vehicle targets.

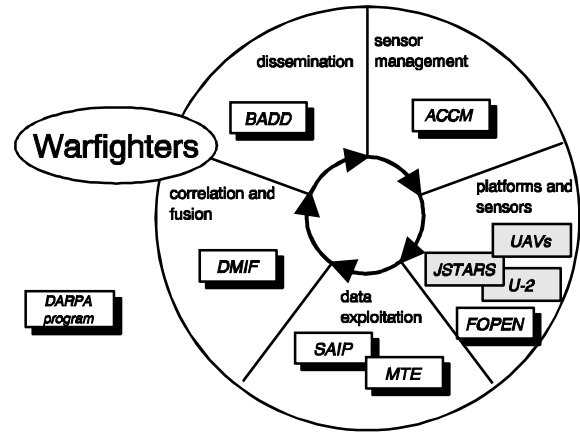


Figure 1. DARPA Technologies in a Surveillance "System of Systems"

THE SYNERGISM OF SAR AND MTI RADAR

Of the many sensors likely to be present in the theater of a future conflict, SAR and MTI will surely be the workhorses, generating a majority of the wide-area-surveillance data. Clearly, they are complementary: SAR can see stationary targets and MTI can only see moving targets. Further, the information gained from one mode enhances the information from the other.

Figure 2 illustrates the synergistic relationship between SAR and MTI. Assume a surveillance operation is underway in which two platforms are viewing a large region — one operates stripmap and spotlight-mode SAR and the other uses MTI, HRR MTI, and ISAR. Assume further that a facility is present which tasks the sensors, fuses the resulting sensor reports, and forms tracks of the detected vehicles. Key is the ability to track a vehicle as it progresses through many "move-stop" cycles. If successful, this reduces the burden of reacquiring and identifying targets as they relocate around the battlefield.

Now consider a vehicle target which begins to move and is detected by MTI. Numerous approaches can be applied in an attempt to classify the moving vehicle. The vehicle's identity may be inferred if its motion characteristics are distinguishable from ambient traffic, for example, if it is in a convoy or battalion.³ If the MTI radar has an HRR or ISAR mode, a range profile or image can be generated and compared to expected target signatures to gain further evidence of the vehicle type.

² A preliminary version of the BADD system is deployed in Bosnia.

³ In many situations, simply identifying a group of vehicles may suffice. For example, it would be unnecessary to identify each vehicle in a particular battalion if the battalion is correctly recognized.

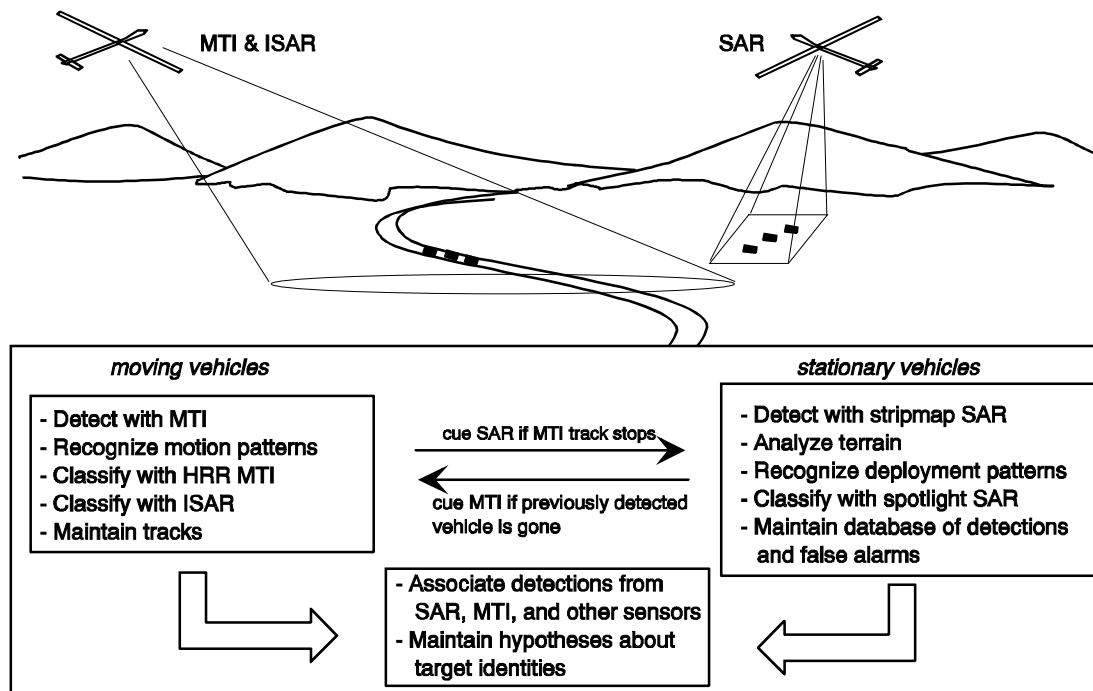


Figure 2. Synergistic Relationship Between SAR and MTI

When the vehicle stops, and the MTI track is lost, the other platform's spotlight SAR mode can be cued to generate a high-resolution image of the area around the lost track. If the vehicle is detected in the SAR imagery and associated with the lost track, the previously obtained evidence about its identity can be applied to the new detection. Analogously, when the vehicle begins to move again, the new MTI track can be associated with the same vehicle seen in the SAR imagery. Once again, the previously gathered evidence about its identity can be carried forward.

The SAR stripmap operation produces a massive library of imagery and, more importantly, a database of targets and false alarms to which subsequent detections can be compared. This database supports a "change-detection" process which enhances the performance of the surveillance operation.⁴ For example, when a SAR views the vicinity around a recently lost MTI track, there may be several vehicles detected in the resulting imagery. If only one of these detections is new, however, it can be associated more confidently with the MTI track.

Of course, in practice, it will be difficult to unambiguously associate every new SAR detection with a lost MTI track and vice versa. Rather, this operation should be conducted with multiple-hypothesis-tracking (MHT) techniques which can maintain many association hypotheses, each with a confidence level [9]. Similarly, ambiguity will exist in the correct identification of each vehicle, so multiple hypotheses about their

identities should be maintained as well. Information from other sensors, such as SIGINT, will also increase the confidence of target identification.

CALCULATING THE EFFECTIVENESS OF SAR AND MTI SURVEILLANCE

The effectiveness of a wide-area-surveillance operation using SAR and MTI is measurable by several parameters, including: (1) the percentage of targets correctly identified and accurately tracked, and (2) the number of non-targets incorrectly identified and tracked as targets. The first measure should be high; the second low.

Myriad factors influence the effectiveness of a surveillance operation and its ability to provide battlefield awareness to the commanders. Is the terrain mountainous, obscuring the view of the sensors? How many "confuser" vehicles are present in the region? How long are the targets exposed? Do they relocate frequently? Do the targets have unique signatures which can be recognized in imagery or range profiles? Are there motion characteristics or deployment patterns which distinguish the targets from clutter?

Because of the complex dynamics and detailed geographic factors, evaluation of the effectiveness of SAR and MTI operations is not amenable to analytic, closed-form calculations; rather, simulation is required. Illustrated in Figure 3, SLAMEM is a simulation built by Toyon Research Corporation specifically for analyzing surveillance and attack operations against high-value mobile targets, such as Scuds. SLAMEM has been applied to evaluate the effectiveness of advanced architectures using SAR and MTI in a number of scenarios, two of which are summarized briefly in the next sections. Although a detailed discussion is beyond the scope of this paper, the results should

⁴ Change detection is a powerful technique to eliminate many repetitive SAR detections from further consideration. If clutter false alarms persist over many looks, they eventually can be "mapped away". The DARPA goal is to achieve a 1,000:1 reduction in clutter false alarms through change detection.

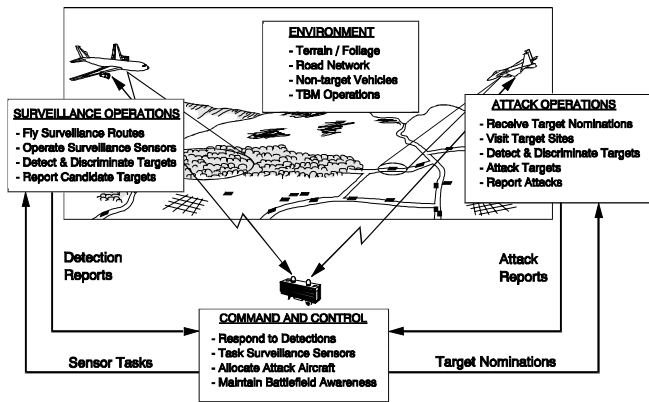


Figure 3. SLAMEM Simulation

provide the reader with insight into the value of SAR and MTI operating together.

ANALYSIS OF “BIRTH-TO-DEATH” TRACKING OF HIGH-VALUE TARGETS

Ideally, a surveillance system could provide the commanders with the identities and locations of all vehicles on the battlefield. Upon entering the region, a vehicle would be immediately identified and subsequently tracked until it left the area or was otherwise deemed no longer to be of interest. We call this birth-to-death tracking.

Scenario and Surveillance Assumptions

A scenario is defined in which ten high-value-target (HVT) vehicles are present on a 10,000 km² battlefield. They relocate often, spending several hours at a location and then up to an hour traveling to the next.⁵ When stopped, the HVTs are exposed.

Many other military and civilian vehicles are also present in the scenario region. To the sensors, a subset of these will resemble the HVTs; we define them to be “confusers”. Clearly, the number of confusers will vary from one scenario region to another and will depend to a large extent upon the performance of the surveillance sensors.

Two high-altitude, radar-equipped UAVs search the region, as shown in Figure 4, one with stripmap SAR, the other using MTI. Those detected objects which are indistinguishable from the HVTs to these sensor modes will be imaged subsequently by high-resolution spotlight SAR, HRR, or ISAR, as appropriate, in an attempt to classify the objects more precisely.

We assume detection and classification performance consistent with DARPA exploitation program goals. Specifically, the density of stripmap-SAR clutter false alarms presented to the image analyst is assumed to be below 0.01 per km². Further, the

⁵ HVTs with the assumed characteristics could include mobile command-and-control posts or mobile air-defense equipment.

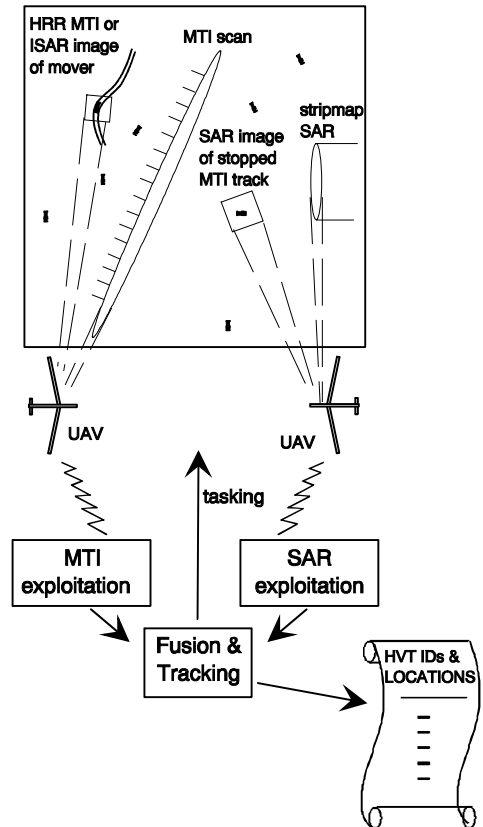


Figure 4. Birth-to-Death Tracking Scenario

HRR MTI and the SAR stripmap mode are able to discriminate well between the HVTs and ambient traffic, leaving an average of 500 non-HVT vehicles (i.e., confusers) which must be classified with the higher resolution spotlight SAR and ISAR modes. These modes are assumed capable of correctly classifying an HVT with 0.9 probability, while incorrectly classifying a confuser as an HVT with 0.1 probability.

The detection and classification results are reported to a centralized location, where algorithms are employed to track all vehicles, HVTs as well as other traffic, and assess their identities. In the analysis, simple spatial and temporal tests decide whether to associate detections with existing tracks or to initiate new tracks. Further, the results of every classification image are combined in a Bayesian manner to initiate and maintain an “HVT-likelihood” for each vehicle in track. Once this probability exceeds a chosen threshold, the vehicle is declared to be an HVT. Thus, a list of current HVT locations is maintained.

Of course, since the sensors and the tracking algorithms are not perfect, not all HVTs will be on the list. The number on the list is controllable, to an extent, by adjusting the acceptance level of the probability threshold. Lowering it allows more of the HVTs to be so declared, but also increases the number of confusers incorrectly classified as HVTs. Raising the threshold results in fewer actual HVTs on the list, but also reduces the number of confusers incorrectly classified. The measure of effectiveness for this analysis will be the average number of HVTs correctly classified and in track, with the threshold set for an equivalent number of incorrectly classified confusers. (Thus,

if the commander decides to strike the objects on the list, no more than one non-target will be hit for each HVT struck.)

Results

To demonstrate the value of SAR and MTI working together, we compare this architecture with the case of equivalent assets using SAR only. Figure 5 shows the number of HVTs classified and in track plotted versus time for each case. Surveillance operations commence at time zero. Over the first six hours the HVT list grows as vehicles are classified until it reaches a steady state with the track-loss rate just offsetting the rate at which new HVTs are classified.

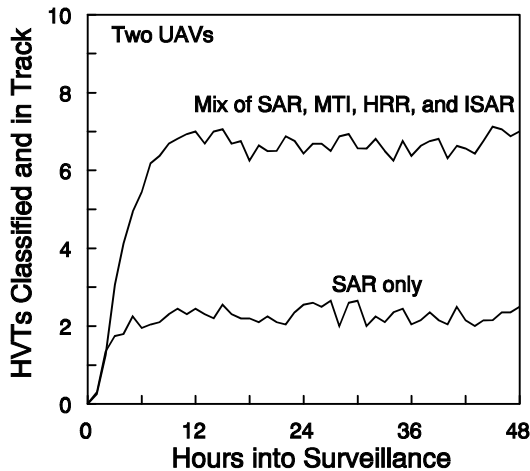


Figure 5. Effectiveness of Birth-to-Death Tracking

With SAR only, the effectiveness is low; only about two of the ten HVTs are classified and in track, on average. Each time an HVT moves, its location and identity are lost until it stops and the SAR finds it again. When in motion, it cannot be tracked. Further, since there is no mechanism for cueing the SAR, the HVT may sit for a long while at its new location before it is reclassified. Alternatively, when SAR and MTI are used together, the effectiveness is significantly better. Once an HVT or other vehicle is identified, the coordination between SAR and MTI allows it to be tracked from one location to the next, thus keeping it on the list much longer. At any moment, on average, seven of the ten HVTs are correctly classified and in track.

The value of SAR and MTI working together in this scenario is clear. Rather than losing each target when it relocates, the MTI provides the ability to track it from one location to the next, preserving and even enhancing the gathered classification information. Next, we explore a more difficult scenario in which the targets remain hidden most of the time.

ANALYSIS OF SAR AND MTI SURVEILLANCE AGAINST MOBILE MISSILE LAUNCHERS

As demonstrated by the Scud-hunting experience in Desert Storm, finding and attacking mobile missile launchers presents an extreme challenge. Their exposure times are very brief. They can operate over a vast area. A significant number of clutter

sources in the region can resemble the transporter-erector-launchers (TELs) to the sensors.

Scenario and Surveillance Assumptions

A canonical mobile-missile scenario is defined in which twenty TELs operate within a mountainous 10,000 km² region. Unlike the HVTs in the previous scenario, the TELs remain hidden most of the time. Each one emerges from hide at some time, independently of the others, and proceeds on the following schedule: travel for fifteen minutes to a launch site, setup over twenty minutes, launch, tear-down in five minutes, and dash for another five minutes to a temporary hide site. The locations of the hide and launch sites are not known a priori to the surveillance operation.

The surveillance system is the same as postulated in the previous section. In this scenario, however, the surveillance information is used for targeting. Once an object is classified as a TEL, by SAR, HRR, or ISAR, it is nominated for attack by an available F-15E aircraft. A total force of 24 F-15Es is assumed to be dedicated to this mission, with approximately four pairs airborne at any time. The F-15Es are assumed to have good discrimination performance, with a 0.95 probability of detecting and correctly classifying a TEL, while only mistakenly declaring a confuser as a TEL ten percent of the time.

Results

Again, two cases are evaluated and compared: UAVs using the SAR mode only, and UAVs using a mix of SAR, MTI, HRR, and ISAR. In the latter case, for simplicity, each UAV is assumed to operate with either SAR or MTI (HRR and ISAR), but not both. The measure of effectiveness is the number of TELs detected, classified, and killed before launch, during an eight-hour interval in which all TELs emerge from hide to attempt one launch. Figure 6 shows the results.

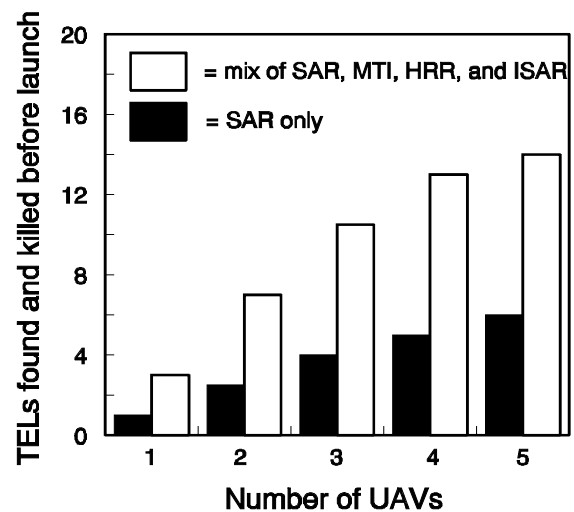


Figure 6. Effectiveness Against Mobile Missiles

When only SAR is used, the effectiveness is limited primarily by the surveillance “revisit time” relative to the TEL

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setup time. Consider the case of a single UAV: with the ten-kilometer SAR swath, it requires at least 100 minutes to cover the entire region. The TEL, on the other hand, launches its missile after spending only twenty minutes stationary at a launch site. The likelihood of imaging the TEL during this brief “window of vulnerability” before launch is low. With more UAVs, the revisit time is reduced proportionally; with five, an average revisit time of twenty minutes is achieved. Even in this case, however, there are frequent occurrences when a TEL is imaged prior to launch, but before it is classified and an F-15E arrives to inspect it, the TEL is able to launch.

Alternatively, with a mix of SAR and MTI, a TEL is much more likely to be detected, classified, and attacked before launch. This approach has two distinct advantages. First, the TEL’s window of vulnerability is lengthened to include the fifteen-minute travel time from hide to the launch site. Some of the TELs can be detected and classified during this interval with MTI, HRR, and ISAR, and then attacked with F-15Es. Second, the MTI can cue the SAR to image the TEL just after it arrives at its launch site. For numerous reasons, a fraction of the TELs will not be classified and attacked during their travel. Nonetheless, a TEL may be recognized as suspicious, based on a range profile for example, and tracked by MTI until it stops at its launch site. One of the SAR platforms is then tasked to image the vicinity around the stopped track. If the TEL is detected and correctly classified, it occurs early in the setup interval, often allowing sufficient time for the F-15Es to arrive, inspect the target, and attack before missile launch.

Although striking TELs before they launch is preferable, any that escape can often be found and attacked by cueing sensors to the estimated location of a detected launch, as provided by DSP satellites, for example. HRR MTI is particularly valuable because it can distinguish between the fleeing TEL and other traffic in the area.

SUMMARY

The pressing need for battlefield awareness in future conflicts underlies the current development of new surveillance platforms, such as the Global Hawk and Dark Star UAVs. They will significantly increase the sensor coverage provided by existing assets, thus making it more critically important to implement the supporting systems and infrastructure necessary to turn the greater quantity of sensor data into useful information for the warfighters. DARPA’s programs are actively developing these necessary support systems.

One of the major focuses is to develop the technologies that will exploit the synergistic nature of SAR and MTI radar. Working together, these modes offer the potential of comprehensive battlefield coverage. In particular, target vehicles will be identified and subsequently tracked as they relocate from one place to another. This capability will provide the commanders, conceptually, with a list of all vehicles on the battlefield. Such precise knowledge of the enemy’s whereabouts and actions will allow more optimal application of force, thus increasing the likelihood of success.

Even in one of the most stressing surveillance scenarios — finding mobile missile launchers — the value of collaborative

SAR and MTI is clear. To find and attack these high-priority targets, the commanders need surveillance assets that can detect and identify the TELs shortly after they emerge from hiding so that sufficient time is available to strike. Together, SAR and MTI provide this ability to “get inside the enemy’s cycle time”.

Of course, many technological advances are needed for this capability to be realized. Of these, several of the more interesting technical challenges are: (1) optimizing the resource-allocation logic for tasking the radar modes; (2) achieving an acceptably low level of clutter false alarms in SAR imagery; (3) developing cost-effective HRR MTI radar to distinguish targets from background traffic; and (4) correctly associating the SAR detections and MTI tracks. DARPA is aggressively addressing these issues through the ACCM, SAIP, MTE, and DMIF programs, respectively.

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